AFOSR-TR-97-0478

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	31 Jan 97	Final report 07/01/92 - 08/31/96

4. TITLE AND SUBTITLE
Fault Tolerant Guarantees of Hard Real - Time Message Deadlines is FDDI Networks

5. FUNDING NUMBERS
F49620-92-J-0385

6. AUTHORS
Wei Zhao

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Texas Engineering Experiment Station
308 Wisenbaker Engineering Research Center
College Station, Texas 77843 - 3000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NM
110 Duncan Ave. Suite B115
Bolling AFB DC 20332 - 0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution Unlimited

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Our project addressed issues relating to fault-tolerant guarantees of message deadlines in communication networks, i.e., even in the presence of a network fault messages will be transmitted before their deadlines.. FDDI(Fiber Distributed Data Interface) networks are well suited for hard real time communications, due not only to their high bandwidth, but also to their bounded token rotation time and dual ring architecture. We extended our results to ATM (Asynchronous Transfer Mode) networks. The project included four development tasks: Delay guarantee methods for fault free situations; Fault management methods; Delay guarantee methods for situations; and extension to ATM networks. One of the bandwidth algorithms designed and analyzed has been officially adopted by the DoD SAFENET.

14. SUBJECT TERMS

15. NUMBER OF PAGES
10

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UNLIMITED

NSN 7540-01-280-5500 Computer Generated STANDARD FORM 298 (Rev 2-89)

Prescribed by ANSI Std 239-18

DTIC QUALITY INSPECTED 3

Final Report

PI Name: Wei Zhao
PI Institution: Texas A&M University
PI Phone Number: 409-845-5098
PI E-mail Address: zhao@cs.tamu.edu
Grant Title: Fault-Tolerant Guarantees of Hard Real-Time Message Deadlines in FDDI Networks
Grant Number: F49620-92-J-0385

Summary

The main focus of our project was thus to address issues related to fault-tolerant guarantees of message deadlines in communication networks, i.e., no matter what happens (even in the presence of a network fault), the messages will be transmitted before their deadlines. We have focused on FDDI (Fiber Distributed Data Interface) networks for this study because they are well suited for hard real-time communications, due not only to their high bandwidth, but also to their property of bounded token rotation time and to their dual ring architecture. We also extend our results into ATM (Asynchronous Transfer Mode) networks. To the best of our knowledge, no previous work in this area has been reported. The project was carried out in four tasks: 1) Development of delay guarantee methods for non faulty situations; 2) Development of fault management methods; 3) Development of delay guarantee methods for faulty situations; 4) Extension to ATM networks. We demonstrated that with the technology we developed, the project objective is successfully achieved. In particular, one of the bandwidth algorithm we designed and analyzed has been officially adopted by the DoD SAFENET.

1. Overview of the Project

High-speed networks are being increasingly deployed in distributed computer systems. These networks may have stringent real-time and fault-tolerance requirements. Besides tolerating an occasional fault caused by component wear-out, these networks must also recover from multiple faults caused by non-natural forces. Consider, for example, a network employed on a battleship to support real-time communication between various on-board devices. An enemy attack may break several communication links in this network. The dual requirements of providing real-time communication and fault-tolerance means that such networks must guarantee the delivery of critical messages on time even in some faulty situations. Designing such networks is a challenging task. The main focus of our project was thus to address issues related to fault-tolerant guarantees of synchronous message deadlines in communication networks, i.e., no matter what happens (even in the presence of a network fault), the messages will be transmitted before their deadlines.

We have focused on FDDI (Fiber Distributed Data Interface) networks for this study because they are well suited for hard real-time communications, due not only to their high bandwidth, but also to their property of bounded token rotation time and to their dual ring architecture. A bounded token rotation time provides a necessary condition to guarantee hard real-time deadlines while the dual ring architecture allows the maintenance of a continuous real-time service under some failure conditions. Although indispensable, the bounded token rotation time and the dual ring architecture alone are inadequate for guaranteeing message deadlines. In addition to these features, synchronous bandwidth allocation also plays a key role in the timely delivery of synchronous messages. Furthermore, under the proposed standard, upon the occurrence of a fault, detection and recovery processes may take several seconds to complete. This is too long to satisfy message deadlines in many hard real-time applications. In this project, we rectified the situation. We also extend our results into ATM (Asynchronous Transfer Mode) networks.

The project was carried out in four tasks: 1) Development of delay guarantee methods for non faulty situations; 2) Development of fault management methods; 3) Development of delay guarantee methods for faulty situations; 4) Extension to ATM networks. The key contributions which made our work innovative and unique are as follows:

- We developed techniques that are able to guarantee message deadlines at *all times*. With our approach, the message deadlines are met before the fault occurs, during fault detection and re-configuration, and after re-configuration. To the best of our knowledge, no previous work in this area has been reported.

- Our approach is compatible with the FDDI and SAFENET standards. Hence, the results obtained from our work are immediately applicable to the design and analysis of distributed hard real-time systems where a SAFENET network is used.

- Our work has contributed significantly to the state of the art in the theory of hard real-time scheduling and communication. We analyzed the system by deriving its worst case utilization bound. This metric is particularly important because it indicates the safety margin of the system and provides a measure of system stability. All previous work regarding this measure is related to the rate monotonic scheduling algorithm. Our work was the very first which derives the worst case utilization bound for a scheduling environment where global priority arbitration is not supported and hence the rate monotonic algorithm cannot be used.

- For ATM networks, we also developed deadline guarantee methods which are compatible with the current products and standards. Hence, we were able to be the first to develop a toolkit (NetEx) that can provide end-to-end deadline guarantees in ATM networks that are currently commercially available.

2. Accomplished Tasks

The P.I. and his graduate students during this project successfully accomplished four research tasks as outlined in the proposal. The major achievement of these tasks are summarized below.

2.1 Delay Guarantees in FDDI Networks

Our method for delay guarantees over FDDI networks is based on synchronous bandwidth allocation. Synchronous bandwidth allocation schemes may be divided into two classes: local allocation schemes and global allocation schemes. These schemes differ in the type of information they may use. A *local* synchronous bandwidth allocation scheme can only use information available locally to node i in allocating H_i. Locally available information at node i includes the parameters of stream S (i.e., C_i, P_i, D_i), and TTRT(Target Token Rotation Time). On the other hand, a *global* synchronous bandwidth allocation scheme can use global information in its allocation of synchronous bandwidth to a node. Global information includes both local information and information regarding the parameters of synchronous message streams originating at other nodes.

A local scheme is preferable from a network management perspective. If the parameters of stream S_i change, then only the synchronous bandwidth S_i of node i needs to be recalculated. The synchronous bandwidths at other nodes do not need to be changed because they were calculated independently. This makes a local scheme flexible and suited for use in dynamic environments where synchronous message streams are dynamically initiated or terminated.

In a global scheme, if the parameters of S_i change, it may be necessary to re-compute the synchronous bandwidths for all nodes. Therefore a global scheme is not well suited for a dynamic environment. In addition, the extra information employed by a global scheme may cause it to handle more traffic than a local scheme. However, it is known that local schemes can perform very closely to the optimal synchronous bandwidth allocation scheme when message deadlines are equal to message periods. Consequently, given the previously demonstrated good performance of local schemes and their desirable network management properties, we concentrate on local synchronous bandwidth allocation schemes in this chapter.

We have proposed and analyzed several local and global synchronous bandwidth allocation schemes. Here we introduce the one that was officially adopted by SAFENET. With this scheme, the synchronous bandwidth for node i is allocated according to the following formula:

$$H_i = \frac{U_i \cdot D_i}{\left\lfloor \frac{D_i}{TTRT} - 1 \right\rfloor} \quad (1)$$

Intuitively, this scheme follows the flow conservation principle. Between the arrival of a message and its absolute deadline, which is D_i time later, node i will have at least $\left\lfloor \frac{D_i}{TTRT} - 1 \right\rfloor \cdot H_i$ of transmission time available for synchronous messages. This transmission time is available regardless of the number of asynchronous messages in the network. During the D_i time, $U_i D_i$ can loosely be regarded as the load on node i. Thus the synchronous bandwidth in (1) is just sufficient to handle the load on node i between the arrival of a message and its deadline. An advantage of using this method is that it comes with a simple deadline guarantee testing procedure: as long as the summation of bandwidths allocated to individual nodes is no more than TTRT, all the messages will meet their deadlines.

2.2 Fault Management in FDDI Networks

As we mentioned earlier, there were some serious problems in the fault-tolerance capability of SAFENET/FDDI architecture, For example, two trunk link faults may disconnect the network, but many mission-critical applications must survive under multiple fault situations. In this part of the project, we aimed at significantly improving the SAFENET/FDDI architecture and hence providing efficient and effective fault-tolerant real-time capabilities.

The basic idea is to use multiple FDDI trunk rings. The space redundancy provided by a multi-ring architecture should improve the system performance. However, the key to fully realizing the potential of this new architecture is to develop good reconfiguration algorithms to handle faults. We developed an architecture called FBRN (FDDI-Based Reconfigurable Network) that consists of r FDDI rings. An FBRN achieves a high degree of fault-tolerance by 1) using multiple FDDI ring networks to connect the hosts and 2) using efficient fault detection and network reconfiguration algorithms.

Fault detection within FBRN is a decentralized process with each FDDI ring performing its standard fault detection operations. Each FDDI trunk ring has its fault recovery mechanism which enables the ring to recover from node faults using the bypass switch and from single point trunk faults using the wrap up operation. FBRN also has a network-level fault recovery mechanism which monitors the available bandwidth in the network and invokes a reconfiguration algorithm when the lower level FDDI-based recovery methods are inadequate. The problem of designing efficient reconfiguration algorithms for FBRN has been extensively addressed [???]. The reconfiguration algorithm is *optimal* in the sense that it always produces a configuration that has the largest number of functional rings for the given fault pattern. One disadvantage of the optimal algorithm is that it requires global information regarding the system fault status. In real-time systems, the communication overheads incurred in collecting this information may be intolerable. The *local* reconfiguration algorithm described [42] does not suffer from this problem. The local algorithm operates in a fully distributed fashion utilizing only locally available information at each node. Further, with this algorithm, the reconfiguration process is transparent to the fault-free rings; the ongoing traffic on these rings is unaffected by the reconfiguration process. Although the local algorithm is not optimal, it is demonstrated to have a near-optimal performance [38].The performance data showed that with our algorithms, the system fault-tolerant capability was greatly improved. For example, with 25% of faulty links, the network, on average, can still provide high bandwidth in comparison with the one without using our methods. Hence, we recommend to employ the local reconfiguration algorithm in practical systems.

2.3 Fault-Tolerant Deadline Guarantees in FDDI Networks

The objective of this part of the project is to provide fault-tolerant real-time management in FBRN. That is to manipulate the network resources and messages so that the deadline guaranteed communication can be provided at

all time. We divide the functionalities of this management into two parts, viz., *off-line management* and *on-line management*. Off-line management involves message assignments, bandwidth allocation and verification that the fault-tolerant real-time requirements can be met. On-line management is responsible for detecting faults, reconfiguring the network in the event of faults, migrating messages from faulty rings to non-faulty ones if necessary, and so on.

For our solution to be practical, we have to minimize the overheads involved in on-line management. Imagine a set of messages already assigned to different rings. At run-time some ring may be detected as faulty. It is the task of on-line management to decide what needs to be done about the messages that were being transmitted on that ring. One approach is to dynamically revise *all* the message-to-ring assignments whenever a ring fault is detected. With this approach, one may be able to fully utilize the network resources while attempting to meet the message requirements. Clearly, this method involves a large run-time overhead and is not practical for real-time applications.

We adopt a *group-based* management approach which deals with message groups rather than individual messages. This approach greatly reduces overheads associated with on-line management. In group-based approach, messages are grouped together based on certain criteria. All messages belonging to a group are assigned to a single ring. With the group-based approach, off-line management is responsible for message grouping, bandwidth allocation and schedulability verification while on-line management is responsible for network initialization, fault detection, network reconfiguration, message group migration and re-initialization.

We observed that the performance of the system critically depends on the message grouping strategies used in off-line management. We considered three approaches: pure *temporal* redundancy, pure *spatial* redundancy and *integrated* approach. Pure temporal redundancy approach uses only one copy of each message but allocates sufficient bandwidth to allow additional time for the message to migrate from one ring to another in the event of a fault. Pure spatial redundancy approach uses multiple copies of the message and assigns them to different rings to achieve fault tolerance. The temporal redundancy approach may require less total bandwidth as compared to the spatial redundancy approach but may sometimes be unfeasible due to excessive message migration overheads. The spatial redundancy approach obviates the need for migration, but may be rendered unfeasible due to excessive bandwidth requirements. Our third approach is an integrated approach that combines both spatial and temporal redundancies. In this approach we transform each message into multiple copies, with at most one copy providing temporal redundancy through allowance for migration. The remaining copies need not migrate and provide spatial redundancy. The integrated approach strikes a balance between bandwidth requirement and migration overheads of pure spatial and pure temporal redundancy approaches and hence outperforms both of them.

In summary, our solution for providing fault-tolerant real-time communication fully exploits the established results on reconfigurability of FDDI-based networks and the real-time capabilities of FDDI.
It is practical because it is modular and easily scaleable and implementable. The network architecture itself is composed using standard FDDI components. The on-line management tasks are implementable in a distributed fashion. The bandwidth allocation scheme is one that is already accepted by the SAFENET standard. The conformance to FDDI and SAFENET standards of our solution is a highlight of this study. Next, we describe our effort to extend these results into ATM networks

2.4 Deadline Guarantees in ATM Networks

ATM is one of the candidate technologies under consideration. Although the proposed ATM standard specifies that ATM should be able to provide bounded delay services, how to best realize such a real-time capability has so far been an open problem. We aimed at addressing this problem in this part of the project. Although it is widely believed that ATM can support real-time traffic, no systematic study has been conducted to provide quantitative analysis and design guidelines for ATM when used as a LAN technology for real-time communications.

We use a decomposition method to derive the delay bound of a cell in an ATM network. With this method, the ATM network is decomposed into a set of servers. A server can be a link, or a component of an ATM switch[1]. Delays of ATM cells at each server are analyzed. The total delay of a cell from a particular connection is then the summation of the delays of servers the connection passes through.

[1] For example, an ATM switch can be decomposed as an input port server, switching fabric server, and an output port server. For a detailed description of decomposition process, see [11, 20].

To successfully apply this methodology, we must have a way to efficiently and effectively specify the traffic in the network. This is because in order to obtain the delay bound at a server, information regarding traffic characteristics at the server entrance must be known. We use the maximum rate function, $\Gamma(I)$ to specify traffic. Formally, $\Gamma(I)$ is defined as the maximum data arrival rate of a connection at any point in the network during a time interval of length I, i.e.,

$$\Gamma(I) = \max_t \left(\frac{\text{Total number of bits arrived in } (t, t+I]}{I} \right)$$

Thus, $\Gamma(I)$ is an "umbrella" function that specifies an upper bound on the arrival rates that may appear in any interval of length I. Different from other traffic descriptors, which usually use a few numerical parameters, $\Gamma(I)$ provides a comprehensive picture of the *worst case demand* placed by a connection over any interval of time. With the input traffic of a server modeled by $\Gamma(I)$, the cell delay at the server can be easily obtained [11]. Furthermore, the characteristics of traffic at the output of a server can be derived in terms of $\Gamma(I)$ as well. This allows recursive analysis of the successive servers.

A problem with using $\Gamma(I)$ as traffic descriptor is that we must know the values of $\Gamma(I)$ for all the values of interval I. Such a comprehensive description of the traffic requires large amount of memory space, which may not be available in practice. To address the problem, approximation methods have been proposed and analyzed [11,21]. In particular, *the point approximation method* [11], in which the values of $\Gamma(I)$ at certain points are stored and others are estimated, was found to be useful. Comprehensive performance evaluation indicates that for a typical networking environment, a 6-point approximation provides the performance that is almost identical to that obtained by using the exact $\Gamma(I)$ values and is much better than using simple bandwidth figures to model the traffic.

In short, using approximated $\Gamma(I)$ to describe traffic of individual connections in the network, we have successfully developed an efficient and effective method for deriving the delay bounds in the network. For the theoretical background on the delay derivation with $\Gamma(I)$, please refer [19,21]. For a discussion on implementation of this delay derivation procedure, please refer [20,24,27]. Once again, our technology is compatible with the existing products. We have designed and implemented a software suite, called *NetEx/ATM*, that can provide delay-guaranteed communication services for mission critical applications over ATM networks. NetEx has been fully tested in our distributed systems lab and is currently being extended into heterogeneous networking domain.

3. Publications

During this project, we have published total 43 referred papers on professional journals, conferences, and edited books. Most of them are available at our web page. Hard copies can also be provided upon request.

3.1 Edited Book Chapters

43. Wei Zhao
Local Area Networks,
Accepted by *Encyclopedia of Science & Technology, 18th Edition, McGra-Hill, 1997.*

42. Wei Zhao
FDDI and its Applications
in *The Communication Handbook*, edited by J. Gibson et al, CRC Press, Dec. 1996.

41. S. Kamat and Wei Zhao
An FDDI-Based Reconfigurable Network for Fault-Tolerant Real-Time Communications
in *Fault-Tolerant Parallel and Distributed Systems*, edited by D. Pradhan and D. Avresky, IEEE Press.

40. S. Kamat and Wei Zhao
Performance Comparison of Two Token Ring Protocols for Real-Time Communications
in *Principle of Real-Time Systems*, edited by S. Son, Prentice Hall, 1995, pp 117 -- 147.

3.2 Referred Journals

39. B. Chen, S. Kamat, and Wei Zhao
Fault-Tolerant Real-Time Communication in FDDI-Based Networks.
To appear in *IEEE Computers*, April 1997.

38. S. Kamat and Wei Zhao
An Efficient Reconfiguration Algorithms for FDDI Based Networks.
IEEE Transactions on Parallel and Distribtued Systems, April 1996.

37. N. Malcolm, S, Kamat, and Wei Zhao
Hard Real-Time Communication in FDDI Networks
Journal of Real-Time Systems, Vol 10 No 1, Jan 1996, pp 75 -- 107.

36. L. Yao, W. Zhao, and C. C. Lim,
A Comparative Study of Three Token Ring Protocols for Real-Time Communications
International Journal on Mini and Microcomputers, Vol. 17, No. 2, 1995, pp 85 -- 97.

35. N. Malcolm and Wei Zhao
Hard Real-Time Communication in Multiple-Access Networks
Journal of Real-Time Systems, Vol. 8, No. 1, Jan 1994, pp 35 -- 77.

19. G. Agrawal, B. Chen, Wei Zhao, and S. Davari,
Guaranteeing Synchronous Message Deadlines with Time Token Medium Access Control Protocol,
IEEE Transactions on Computers, Vol. 43, No. 3, March 1994, pp 327--339.

34. N. Malcolm and Wei Zhao
The Timed Token Protocol for Real-Time Communication
IEEE Computers, Vo. 27, No. 1, Jan 1994, pp 35 --41.

33. S. Natarajan and Wei Zhao
Building Dynamic Hard Real-Time Systems,
IEEE Software, Sept 1992, pp 16 -- 21.

3.3 Referred Conferences

32. A Sahoo, B. Chen, and Wei Zhao
Connection-Oriented Communications for Real-Time Applications in FDD-ATM-FDDI Heterogeneous Networks
Proc. of the IEEE International Conference on Distributed Computing Systems, May 1997.

31. C. Li, A. Raha and Wei Zhao
Stability in ATM Networks.
Proc. of the IEEE International Conference on Computer Communications, April 1997.

30. A. Sahoo, Wei Zhao, and B. Chen
Resource Allocation for Multi-Media Communication in Heterogeneous Network
Proc. of the IEEE Workshop on Resource Allocation for Multi-Media Systems, Dec. 1996.

29. B. Chen, Y. Zhang, J. Yen, and Wei Zhao

Fuzzy Adaptive Connection Admission Control for Real-Time Applications in ATM-Based Heterogeneous Networks
Proc. of the IEEE International Conference on Fuzzy Logic and Industrial Control Applications, Nov. 1996.

28. Wei Zhao and B. Chen
On Guaranteeing Message Deadlines in ATM-Based Heterogeneous Networks
Proc. of International Conference of Computing Science, Oct 1996.

27. F. Feng, C. Li, A. Raha, S. Yu and Wei Zhao
Modeling and Regulation of Host Traffic in ATM Networks for Hard Real-Time Applications
Proc. of the IEEE Conference on Local Computer Networks, Oct 1996

26. Z. Wang, S. Davari, G. Collins, and W. Zhao
Using Asynchronous Mode of FDDI to Support Real-Time Multi-media Communication
Proc. of the 4th International Workshop on Parallel and Distributed Real-Time Systems, April 1996

25. R. Raha, S. Kamat, and Wei Zhao
Admission Control for Hard Real-Time Connections in ATM LAN
Proc. of IEEE International Conference on Computer Communications, March 1996.

24. F. Feng, A. Kumar, and Wei Zhao
Bounding Application-to-Application Delays for Multimedia Traffic in FDDI-Based Communication Systems
Proc. of the SPIE International Symposium in Electronic Imaging, Feb 1996.

23. B. Chen, S. Kamat, and Wei Zhao
Fault-tolerant Real-Time Communication in FDDI-Based Networks
Proc. of IEEE Real-Time Symposium, Dec. 1995.

22. A. Raha, N. Malcolm, and Wei Zhao
Hard Real-Time Communications with Weighted Round Robin Service in ATM Local Area Networks
Prof. of the First IEEE International Conference on Engineering of Complex Computer Systems (ICECCS'95),
Nov. 1995.

21. A. Raha, S. Kamat, and Wei Zhao
Using Traffic Regulation to Meet End-to-End Deadlines in ATM Networks,
Proc. of IEEE Conference on Network Protocols, Nov. 1995.

20. F. Feng, K. Sanjay, and Wei Zhao
Guaranteeing Application-to-Application Deadlines in Distributed Real-Time Systems
Proc. of IEEE Conference on Local Computer Networks, Oct. 1995.

19. A. Raha, S. Kamat, W. Zhao,
Guaranteeing End-to-End Deadlines in ATM Networks
Proc. of the IEEE International Conference on Distributed Computing Systems, May 1995.

18. A. Raha, N. Malcolm, W. Zhao,
Performance Evaluation of Admission Policies in ATM Based Embedded Real-Time Systems
Proc. of IEEE Conference on Local Computer Networks, Oct. 1994, pp 129-138.

17. S. Kamat and Wei Zhao

An FDDI-Based Reconfigurable Network for Fault-Tolerant Real-Time Communications
IEEE Workshop on Fault-Tolerant Parallel and Distributed Systems, June 1994.

16. B. Chen, H. Li, and Wei Zhao
Some Timing Properties of Timed Token Medium Access Control Protocol
Proc. of International Conference on Communication Technology, June 1994, pp 1416 - 1419.

15. L. Yao, W. Zhao, and C. Lim
Performance of Three Token Ring Protocols for Real-Time Communications
Proc. of International Conference on Communication Technology, June 1994, pp 605 - 608.

14. S. Kamat, G. Agrawal, and Wei Zhao
On Available Bandwidth in FDDI-Based Reconfigurable Networks
Proc. of IEEE International Conference on Computer Communications, June 1994.

13. Wei Zhao, A. Kumar, G. Agrawal, S. Kamat, N. Malcolm, and B. Chen
Real-Time Communication in FDDI-Based Reconfigurable Networks.
Proc. of IEEE Workshop of Real-Time Operating Systems, May 1994, pp 49 -- pp 52.

12. G. Agrawal, S. Kamat, and Wei Zhao
Architectural Support for FDDI-Based REconfigurable Networks
Proc. of IEEE Workshop on Architectures for Real-Time Applications, April 1994.

11. S. Kamat, N. Malcolm, and W. Zhao
Performance Evaluation of Synchronous Bandwidth Allocation Algorithms for Real-Time Messages with Arbitrary Deadlines, *Proc. of IEEE Symposium on Real-Time Sysmtems*, Dec. 1993, pp 34 -- 43.

10. A. Goforth, S. Natarajan, and Wei Zhao
R-Shell: A New Approach of Resource Management for Distributed Real-Time Systems
Proc. of AIAA Conference on Computing in Aerospace, Oct. 1993, pp 383 -- 389.

9. N. Malcolm and W. Zhao
Guaranteeing Synchronous Messages with Arbitrary Deadline Constraints
Proc. of IEEE Conference on Local Computer Networks, Sept. 1993, pp 186 -- 195.

8. S. Kamat and W. Zhao
On Probability of Guaranteeing Synchronous Real-Time Messages in an FDDI Network
Proc. of 2nd International Conference on Computer Communications and Networks, June 1993, pp 26 -- 32.

7. S. Davari, T. Leibfried Jr., S. Natarajan, D. Pruett, L. Sha, and Wei Zhao
Real-Time Issues in the Design of the Data Management System for Space Station Freedom
Proc. of First IEEE Workshop on Real-Time Applications, May 1993, pp 161 -- 165.

6. S. Natarajan and Wei Zhao
Cooperative Resource Management in R-Shell
Proc. of IEEE Workshop of Real-Time Operating Systems, May 1993, pp 44 -- 50.

5. S. Kamat and Wei Zhao
Schedulability of Two Token Ring Protocols for Synchroonous Real-Time Messages
Proc. of the IEEE International Conference on Distributed Computing Systems, May 1993, pp 26 -- 32.

4. G. Agrawal, B. Chen, and Wei Zhao,
   Local Synchronous Ca[acity Allocation Schemes for Guaranteeing Message Deadlines with the Timed Token Protocol
   Proc. of the IEEE International Conference on Computer Communications, March 1993, pp 186 -- 193.

3. L. Yao, W. Zhao, and C. Lim
   An Efficient Window Window Protocol for Real-Time Communications in Token Ring Networks.
   Proc. of IEEE 2nd International Conference on Computer Science, Dec. 1992, pp 231 -- 238.

2. B. Chen, G. Agrawal, and Wei Zhao
   Optimal Synchronous Capacity Allocation with the Timed Token Protocols for Hard Real-Time Communications
   Proc. of IEEE Real-Time Systems Symposium, Dec. 1992, pp 198-207.

1. P. Alexander, C. Lim, J. Liu, and Wei Zhao
   Managing Transient Overload in an Imprecise Computation System
   Proc. of the IEEE Workshop on Imprecise and Approximate Computation, Dec 1992, pp 1 -- 5.

4. Professional Personnel

The following graduate students actively participated in the project and successfully got their degrees, and are currently working in the high tech industry or universities.

A. Ph.D. Students Graduated
- Lijun Yao, Asynchronous hard real-time communications in token ring networks, Dec 1994
- Nicholas Malcolm, Hard real-time communication in high speed networks, Dec 1994.
- Sanjay Kamat, Performance of high speed networks for real-time applications, Dec 1995
- Raha Amitava, Integrated Scheduling with high speed local area networks, Aug., 1996.
- Fang Feng, Integrated Scheduling with high speed ATM networks, June 1996.
- Biao Chen, Optimal resource management in distributed computing systems, Aug., 1996.

B. Master Students Graduated
- Vinay Purohit, A Simulation and visualization tool for the MDM-BIU Subsystem on the space-station Freedom, Aug 1993.
- Mir Asad Ali Khan, Scheduling in multi-processor real-time systems, May 1994.
- Purvi Gajiwala, A simulation study of high speed networks for periodic real-time traffic, May 1994.
- Rakesh Burudgunte, Design and implementation of a token ring device driver for Lynx Operating system, May 1994.
- Amit Kumar, Real-time communications with of FDDI token ring networks, May 1995.
- Hong Li, Performance evaluation of bandwidth allocation algorithms for FDDI networks, Dec. 1995.
- Dwight Tomkins, A simulation study on ATM networks, Dec. 1995.
- Shiqian Yu, Use of ATM networks for real-time applications, May 1996.

5. Significant Events and Professional Awards

5.1 Inventions

2. Wei Zhao, B. Chen, and G. Agrawal
   Local Synchronous Bandwidth Allocation in a Token Ring Network

U.S. Patent, issued in May 1994.

1. Wei Zhao, G. Agrawal, B. Chen, S. Davari,
Normalized Proportional Synchronous Bandwidth Allocation in a Token Ring Network
U.S. Patent, issued in Dec. 1994.

5.2 Honors/Awards

4. Honor/Award: Keynote Speaker
   Year Received: 1994
   Honor/Award Recipient(s): Wei Zhao
   Awarding Organization: IEEE International Workshop on Parallel and Distributed Real-Time Systems

3. Honor/Award: TEES Fellow
   Year Received: 1993
   Honor/Award Recipient(s): Wei Zhao
   Awarding Organization: College of Engineering, Texas A&M Univ. and Texas Engineering Experiment Station

2. Honor/Award: Faculty Recognition
   Year Received: 1993
   Honor/Award Recipient(s): Wei Zhao
   Awarding Organization: College of Engineering, Texas A&M Univ. and Texas Engineering Experiment Station

1. Honor/Award: Outstanding Paper Award
   Year Received: 1992
   Honor/Award Recipient(s): Wei Zhao, B. Chen, G. Agrawal, S. Davarri
   Awarding Organization: IEEE International Conference on Distributed Computing Systems

5.3 Interactions

1. With CISCO and Baynetworks on using their source code of the FDDI and ATM networks in order to implementing our methods on real-time communications over FDDI and ATM networks. Both agreed to provide the source code as well as engineer's support. The total support is worth cash equivalent to more than $100,000.
2. The P.I. actively participated in the DoD NGCR program. Specially, the P.I. presented the research results with SAFENT and HPN working groups and discussed with the members of the working groups about utilizing them. As a result, SAFENET officially adopted one of the bandwidth allocation algorithm invented by the P.I. and his students.